NEUTRAL CURRENTS IN THREE-PHASE ALTERNATORS & TRANSFORMERS

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A study of neutral currents
in star connected

A STUDY OF NEUTRAL CURRENTS IN STAR CONNECTED THREE - PHASE ALTERNATORS AND TRANSFORMERS

A THESIS

PRESENTED BY

EVERETT DEE KAISER

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" "	Oct. 14, 1909
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London Electrician	Jan. 25, 1907
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Electric Journal	Sept., 1906
" "	Apr., 1907
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Electrical Engineer	Apr. 24, 1908
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INTRODUCTION.

With the widespread growth of electrical industries and the multiplication of the uses to which electricity may be put, has come the demand for more and more efficient methods of transmission. The scope of work with direct current was soon found to be limited to a few miles at most from its point of generation. Alternating current solved the problem of long distance transmission by giving us an easy method of obtaining any desired change in voltage by the use of transformers.

Thus, alternating current has enabled central stations to be operated which supply the electrical power for whole cities, or for large districts. Alternating current is now used everywhere for power transmission. It is a standard, because this method of generation, transmission and application of

electrical energy has proven to be by far the most efficient as regards losses in operation, the most ecenomical as regards first cost, and the most adaptable to the various uses to which it is to be put. It has proven especially valuable in developing the water power resources of the world because of its ease of transmission. It has brought the power of the waterfall and the mountain stream to places where it can be used.

In their efforts to increase the range over which power may be economically transmitted, engineers are continually attempting the use of higher and higher alternating voltages. These high voltages of course necessitate the use of thicker, better and altogether more expensive insulation. above certain values of voltage the cost of proper insulation and protection has proven to be almost prohibitive. The question of insul-

ation is one of the most important in planning for high voltage transmission.

The work of engineers to reduce as much as possible the cost of insulation has had much to do in bringing about the general use of star connected generators and transformers. With the star connected alternator the voltage to be insulated against between line and ground - providing the neutral is grounded - is that of each coil in the generator, while if the machine were delta connected and generating the same line voltage there is the possibility that the the voltage to ground from two of the lines will be equal to the line voltage, or 1.732 times that with the star connected machine.

Another point probably equally important in favor of the star connected alternator is the fact that , using the same windings in the alternator, the star connection

will give a voltage 1.732 times that using a delta connection, and with the same safety as regards insulation. Or, turning it around, if we wish to keep the line voltage the same the voltage to be insulated against in the alternator windings using the delta connection will be 1.732 times that where the star connection is used. This means that a great saving may be effected in the construction of alternators by using the star connection. There is also a possibility that there may be a saving in the weight of iron used in the core, but this is somewhat doubtful. For the same line currents the two machines will have the same capacity, and the weight of copper in the windings will also be the same. However the saving in insulation alone has caused the star connection to be used almost universally.

These benefits of the star connection

are, of course, to be had only when the neutral point of the winding is lead out and grounded. At least, it must be connected to that element or part of the apparatus from which it is necessary to insulate. If this is not done there is a possibility that the point of zero potential may become displaced and bring great strain on the insulation of one or more lines of the transmission line, or of coils of the alternator.

When attempts were first made to operate alternators in parallel with the neutrals of both machines connected to ground a great deal of trouble was experienced. It was found that under certain conditions an enormous current was set up in the neutral, and that currents of one-third that value appeared in the line wires. Numerous severe accidents were met with at first, and as a result, a great deal of experimenting and study was done on this subject by those inter-

ested. The following is a brief summary of the investigations of some of the men who have studied the cause and action of neutral currents.

E.W. Marchant and J. K. Catterson-Smyth in an article printed in " The Electrician ", August 6, 1909, explain the following points concerning the neutral currents in star connected apparatus.

(1) The neutral currents are due to the resultant voltages of higher frequency than the fundamental. The alternating current generator windings are separated by 60 electrical space degrees so that the e.m.f's generated are identical in wave form but their maximum points are separated by 60 electrical time degrees. Hence the line voltage cannot contain triple harmonics or its multiples for the addition of the line voltage waves at 60 degrees difference in phase cancels all the harmonics that have a frequency that is a multiple of three.

(2) There can be no triple frequency currents or its multiples unless the neutrals of the system are connected directly or through the ground. If a neutral connection is provided between the machines and the phase e.m.f. wave forms of the machines differ the local circuits will carry currents due to the resultant of the e.m.f's of higher frequency. The triple frequency currents in each machine are in phase with each other, provided the windings are symmetrical, hence the current flowing in each neutral will be three times as large as the triple frequency current in each winding.

In the " Electric Journal " for April 1907, Geo. I. Rhodes explains that these local currents may be caused by phase displacement between the machines, or a change of magnitude or frequency of one of the generators. These changes may be caused by a change in excitation, a momentary fluctuation of angular velocity, or by a permanent

change in driving torque of one of the machines.

(3) A three phase winding is as a whole non-inductive to triple frequency currents if each phase carries a triple frequency current of equal magnitude, unless there is an appreciable amount of slot leakage flux. The adjacent coils neutralize each other as far as any magnetomotive force acting on the main magnetic circuit due to the triple frequency current is concerned, so that the only reactance to the triple frequency currents is the slot leakage reactance. The amount of the slot leakage flux depends upon the shape of the slots, the length of the air gap, the distribution of the winding, and the total number of conductors. For a given voltage at a frequency the turbo-alternator, in comparison with the slow speed alternator, has fewer stator conductors, wide slots, and a long air gap,

hence the triple frequency phenomena have been more noticeable in the turbo-alternator system . While it is possible that a current of any frequency , which is a multiple of three times the fundamental frequency, should flow around the local circuit, it is always likely that the main component will be of triple frequency since the reactance due to slot leakage will be proportional to the frquency and will therefore tend to decrease the current components as the frequency increases.

(4) The neutral currents cause additional heating in the machine windings and reduce the power factor of the machine carrying them. The method of determining the best power factor for any individual machine coupled to the busses would be to find the excitation at which the current flowing through its neutral is a minimum.

PROPOSED EXPERIMENTS.

With the available laboratory apparatus we wish to make a close study of the neutral current phenomena in three-phase star connected apparatus. A list of the apparatus at our disposal and of the proposed experiments follow.

Apparatus:

#1 - Alternating Current Generator #65446
Made by the General Electric Company.
Type A T B
Class 6 - 15 - 1200
Form B Amperes - 72. Full Load V. - 120.

#2 - Alternating Current Generator #65447
Same specifications as # 65446.

#3 - Alternating Current Generator #38248.
Made by the Western Electric Company.

Type S 5 B 0	1200 R. P. M.
30 K.W.	1100 Volts.
3 Phase.	60 cycles.

Three-Phase Transformer # 268498.

Made by General Electric Company.

Type H Form A.

15 K.W. 25 Cycles.

Volts 1100/1905 - 110/220/440.

Core Type.

Three Similar Single-Phase Transformers.

Made by the General Electric Company.

Nos. 229426 - 229427 - 229428 .

Type H. Form E. 25 Cycles.

Volts 1100/2200 - 110/220/440 .

5 K.W. Core Type.

Three Similar Single-Phase Transformers.

Made by the Westinghouse Electric & M'f'g Co.

Nos. 123782 - 123783 - 123784 .

Style 10171.

Volts 1050 - 420/210

5 K.W. Shell Type.

The Oscillograph.

Ammeters.

Voltmeters.

Rheostats.

Frequency Meters.

Lamp Banks.

Experiments:

No. 1 -

To study the effects on the wave shape and value of neutral currents between two similar alternators running in parallel caused by exciting them to give various differences in voltage, and also the effect of operating them in parallel with a permanemt phase displacement between them.

No. 2 -

To study the neutral current interchanged between an alternator and a set of three single-phase shell type transformers connected star. Repeat using core type instead of shell type transformers and compare

the results of the two tests.

No. 3 -

To investigate the effect upon the shape and value of neutral current waves between an alternator and a set of single-phase shell type transformers due to the operation of the transformers at various flux densities up to above normal value.

No. 4 -

To operate in parallel two alternators having dissimilar characteristics and study the current which flows in the connection between their neutrals.

No. 5 -

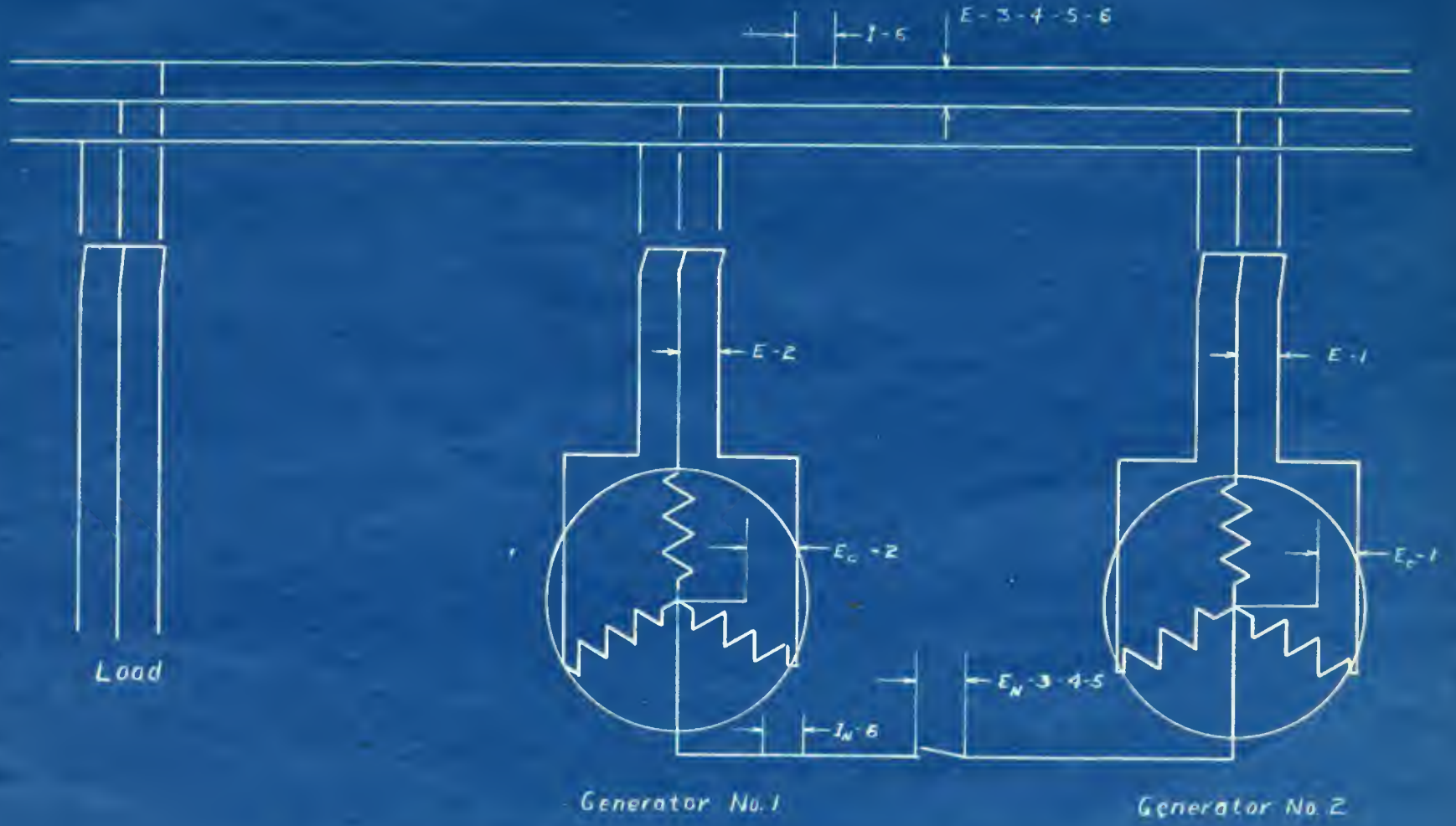
To study the neutral current with respect to wave shape and value which flows between the neutrals of an alternator and a three-phase transformer to which the alternator is connected. Various excitations are to be used, and a comparison made with the results obtained in experiment No. 3.

Experiment No. 1.

In this experiment generators No. 1 and No. 2 are operated in parallel. Each generator is driven by a direct current shunt wound motor. The motors are supplied from the same system. This direct current system carries the regular house lighting and power load, and on account of this fact the parallel operation of the two generators is not very satisfactory.

By means of the oscillograph the wave shape of coil and line voltage of each machine is obtained. Then the two machines are synchronized, the neutral being open, and a study made of the effect upon the neutral voltage between machines caused by varying the fields of the two generators. In order to exaggerate the neutral voltage one machine is motored slightly by strengthening its direct current motor field. Oscillograms of the voltages are taken, but on account of

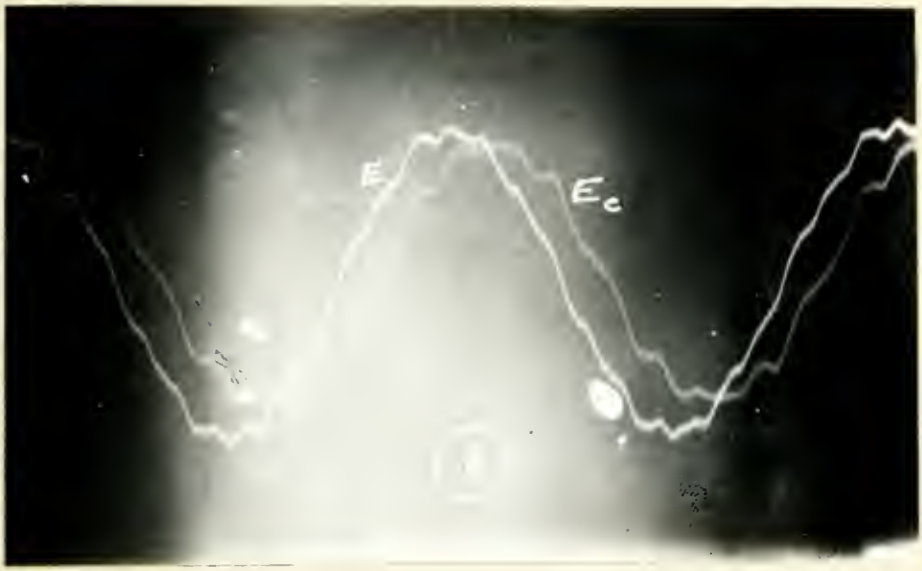
the unsteadiness of the direct current supply it is impossible to keep conditions constant long enough to observe the different values of voltage and current. Next a balanced load of incandescent lamps is fed from the bus bars of the two generators operating in parallel with neutral closed, and the wave form of the line current and neutral current is obtained.



Connections for Experiment No. Oscillograms Nos. 1-2-3-4-5-6

Oscillogram No. 1 shows the coil and line voltage wave shapes of generator No. 2. This was photographed with the machine normally excited and running at 60 cycles. E is the line voltage, and E_c is the coil voltage. An examination of the curves shows that the line voltage contains a thirteenth harmonic and the coil voltage contains a ninth. The fact that no third or multiple of the third appears in the line voltage while a ninth does show in the coil voltage bears out the statement made by Marchant and Catterson-Smyth as quoted in the introduction.

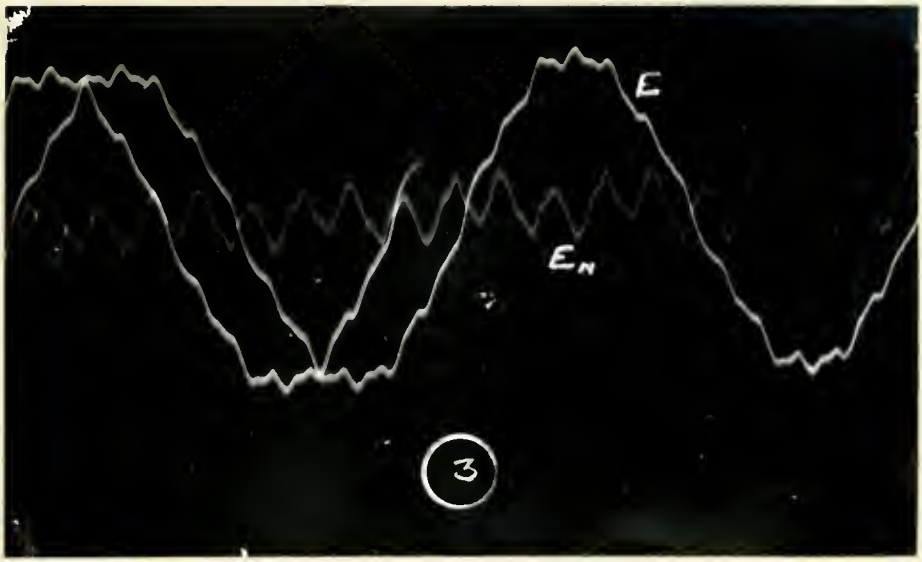
Oscillogram No. 2 shows the coil and line voltage wave shapes of generator No. 1 photographed under normal conditions of operation. Generators No. 1 and No. 2 are of similar design and size, and being operated under the same conditions, the wave shapes are practically the same. As with generator No. 2, the line voltage shows the thirteenth harmonic and the coil voltage shows a ninth harmonic.

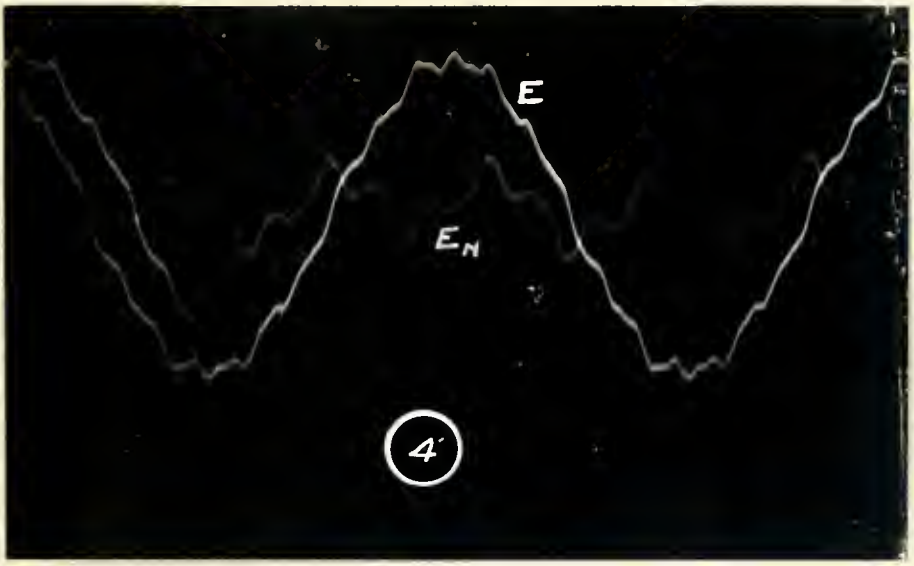

E
E_c

E_c
E
2

Oscillogram No. 3 is a photograph of the wave shapes of bus bar voltage and voltage between generator neutrals taken with the machines operating in parallel. E is the bus bar voltage wave and E_n is the wave of voltage between neutrals. The extra wave is a partial repetition of the bus bar voltage caused by the shutter remaining open for more than one revolution of the film cylinder. The bus bar voltage wave is shown to be practically the same in shape as the line voltage wave of each machine when operated alone. The thirteenth harmonic appears quite distinctly. The voltage between neutrals shows a comparatively strong ninth harmonic and a third of small value. According to Marchant and Catterson-Smyth the third is ordinarily larger than the ninth but in this case the ninth harmonic is much larger than the third. However the statement made by these gentlemen that the neutral current consists only of a third and multiples thereof is borne out.

Oscillogram No. 4 again shows the bus bar voltage, E, and the voltage between neutrals, E_n. This shows the effect on the neutral voltage of operating the two alternators in parallel with their field excitations different. Before paralleling , the field of No. 1 was adjusted to give 120 volts and No. 2 field to give 100 volts. After paralleling , the bus bar voltage was 110 volts and the voltage between neutrals1.5 volts. This condition of operation apparently has no effect on the bus bar voltage for the wave shape is practically the same as obtained in the previous oscillogram. The neutral voltage wave still shows the presence of a third and a ninth harmonic but in this case the third is of much the greater value. Next, the machines were paralled with their voltages adjusted to 130 and 90 volts. After paralleling , the bus bar voltage was 110 volts and the voltage between neutrals 3 volts.


E
E_N
3


E
E_N
4

Oscillogram No. 5 is a photograph of the bus bar voltage wave with No. 1 and No. 2 alternators operating in parallel, and the voltage wave between their neutrals. In order to study the effect of phase displacement between the alternators upon the neutral voltage, the shunt firld of the motor driving No. 1 generator was strengthened slightly so as to cause No. 1 generator to motor. Due to the unsteadiness of the house supply from which the direct current motors were supplied, steady operating conditions could not be obtained. At times the exchange of current between the machines was excessive, and this accounts for the peculiar conditions shown in the photograph.

For some unexplainable reason there is a ninth harmonic appearing in the bus bar voltage. The neutral voltage wave still shows the third and ninth harmonics. The

third is of much greater value than the ninth. By a comparison of oscillograms No. 3, No. 4, and No. 5 it is evident that as the neutral voltage increases the third harmonic becomes more predominant and tends to determine the neutral wave shape. This fact is clearly shown in oscillogram No. 5.

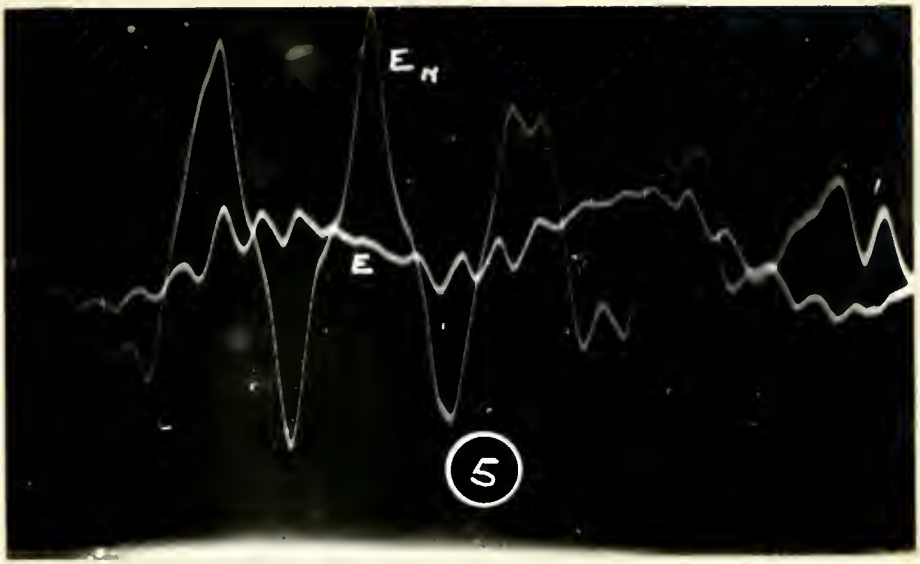
Oscillogram No. 6 shows the neutral current between alternators No. 1 and No. 2 operating in parallel, the bus bar voltage, and the line current feeding a balanced incandescent lamp load. E is the bus bar voltage, I is the line current, and I_n is the neutral current.

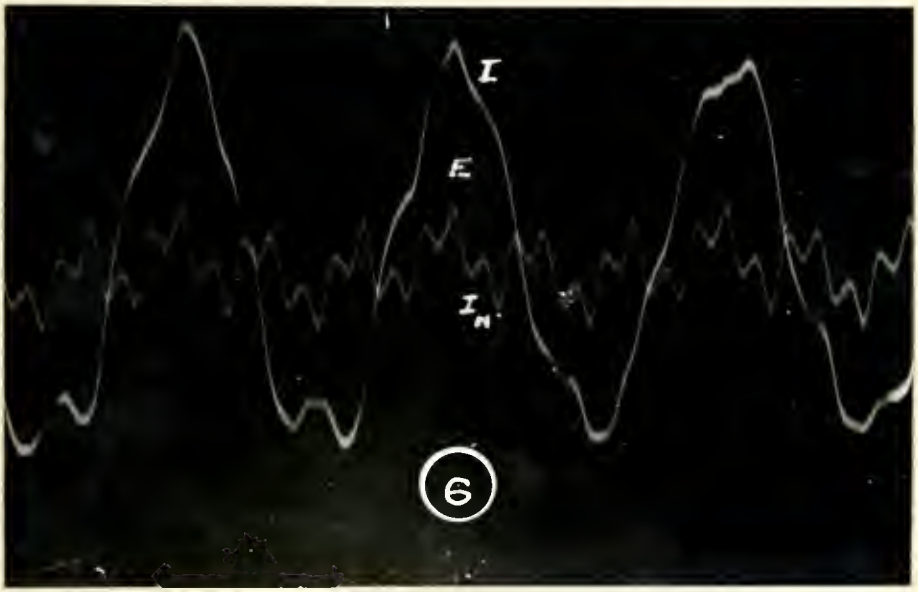
E = 110 volts

I = 21.5 amperes

I_n = 4 amperes

The neutral current is made up of a third harmonic, a ninth, and a small fundamental. The presence of this fundamental in the neutral may be accounted for by a difference of resistance in the leads connecting the alternators, by a slight difference in generated coil voltage, or by an unbalanced load. Any one of these conditions would allow part of the line current to return on the neutral connection.


E_M
E
5

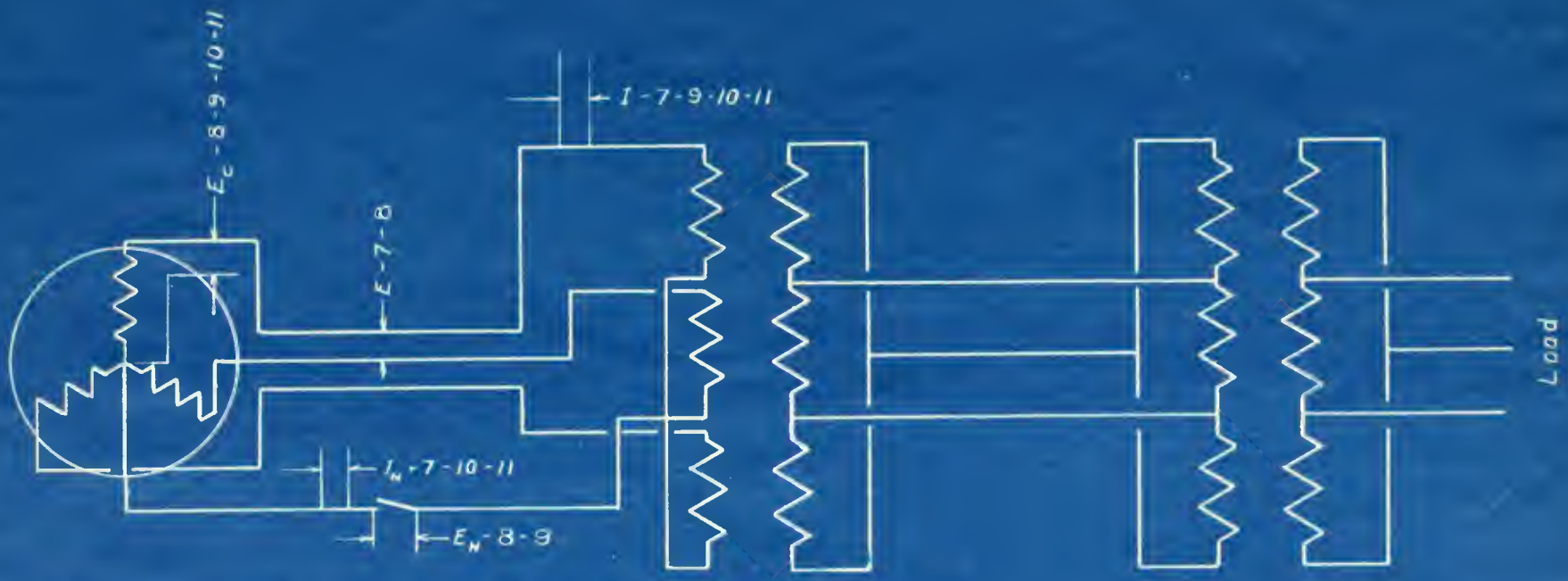

I
E
I_M
6

Experiment No. 2.

In experiment No. 2, alternator No. 2 is connected in star to the low side of a set of three star connected shell type single-phase 10 : 1 transformers. The secondaries of the transformers are connected delta to a 10 : 1 three-phase transformer in order to step down the voltage to feed a load. All values and wave shapes are taken between the generator and the transformers with no load, and with the neutral between the generator and set of transformers open.

The shapes and values of the line voltage , the voltage from line to neutral, the voltage between neutrals, and the line or exciting current are obtained. Then with the neutral closed and no load on the transformers, the values and shapes of the neutral current, the line current, and the coil voltage are obtained. A balanced lamp load is then connected and again the values and

shapes of the line current , the neutral current , and the coil voltage are obtained. In order to compare core and shell type transformers a set of core type transformers is substituted for the shell type , the method of connection being kept as before, and with a balanced lamp load connected the values and shapes of line voltage , line current , and neutral current are obtained.

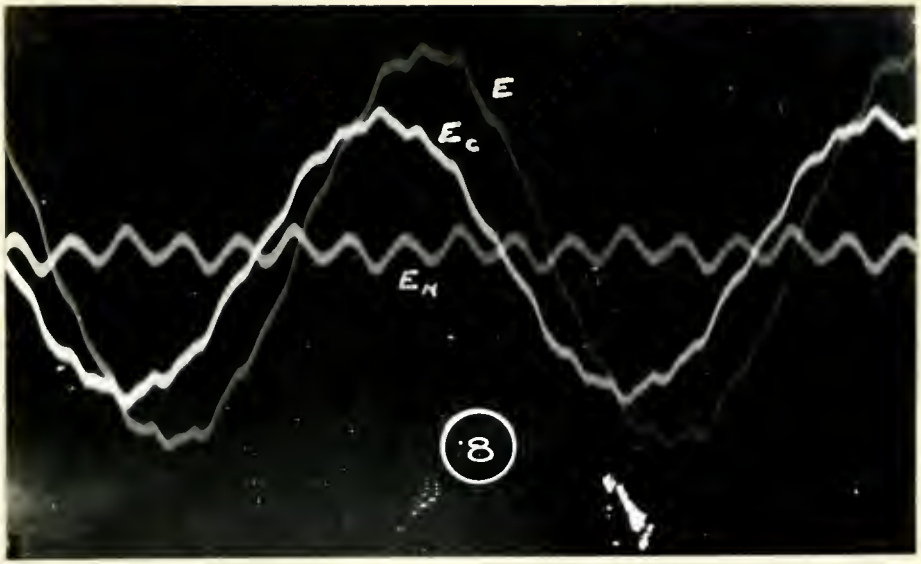


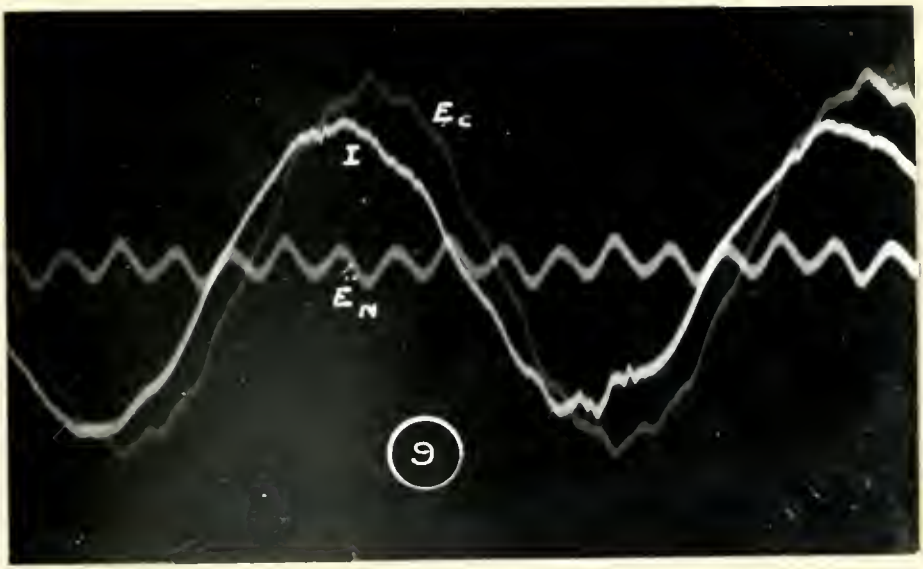
Generator No. 2 — 3 Single Phase Shell-type Transformers — 3-Phase Transformer

Connections for Experiment No. 2 Oscillograms Nos. 7-8-9-10-11

Oscillogram No.8 shows the following wave shapes: line voltage , coil voltage , and voltage between the generator neutral and the transformer neutral. The line voltage shows a thirteenth harmonic. This is also true of the coil voltage . The neutral is composed of a ninth harmonic and a small third.

Oscillogram No. 9 is a photograph of the wave shapes of coil voltage , voltage between neutrals , and of the transformer exciting current when the neutrals are not connected. The value of the exciting current was 1.3 amperes.


E
E_c
E_M
8


E_c
I
E_M
9

The effect of closing the neutral connection upon the exciting current is plainly shown in oscillogram No. 10. The value of exciting current increased from 1.3 to 2.4 amperes. The shape of the exciting current wave with neutrals open was approximately a sine wave as shown in oscillogram No. 9. With the neutrals closed , that portion of the neutral current which returns on the line has badly distorted the line current wave. The neutral current wave is made up of a strong ninth harmonic and a weak third and has introduced these harmonics into the line current wave. The value of the neutral current was 6.3 amperes.

Oscillogram No. 11 shows the effect on the neutral and line current wave shapes caused by supplying a balanced incandescent lamp load from the transformers. As before the waves are of line current , neutral current , and coil voltage.

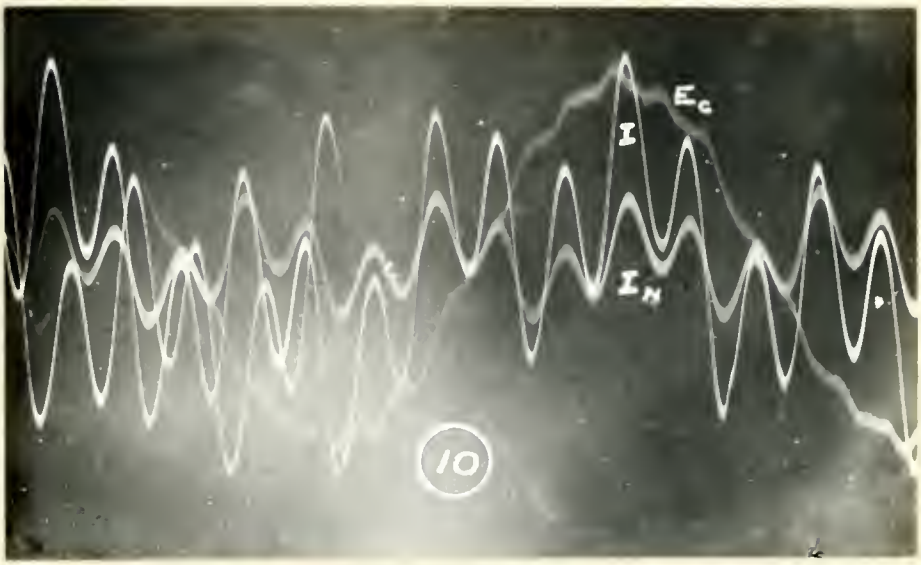
Line current = 10.6 amperes

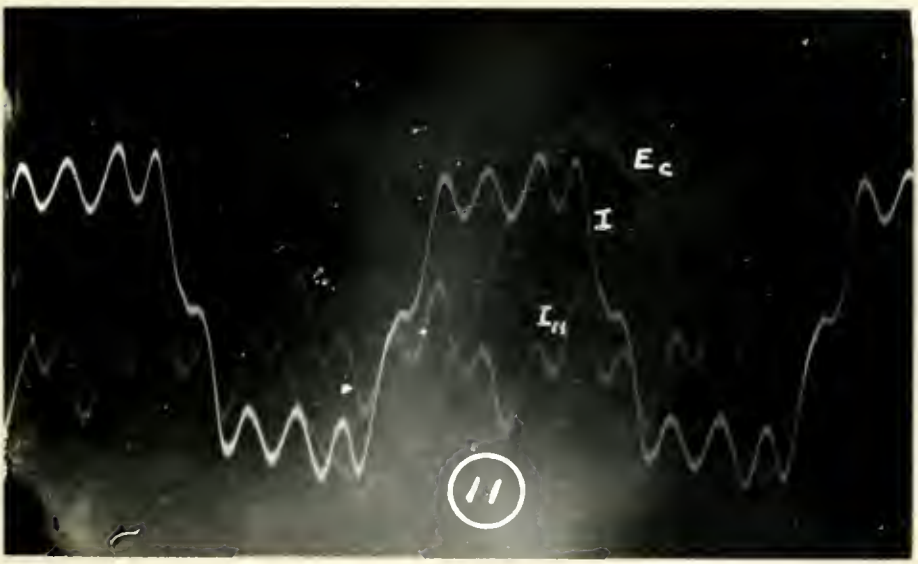
Neutral " = 9 "

Coil voltage = 68 volts.

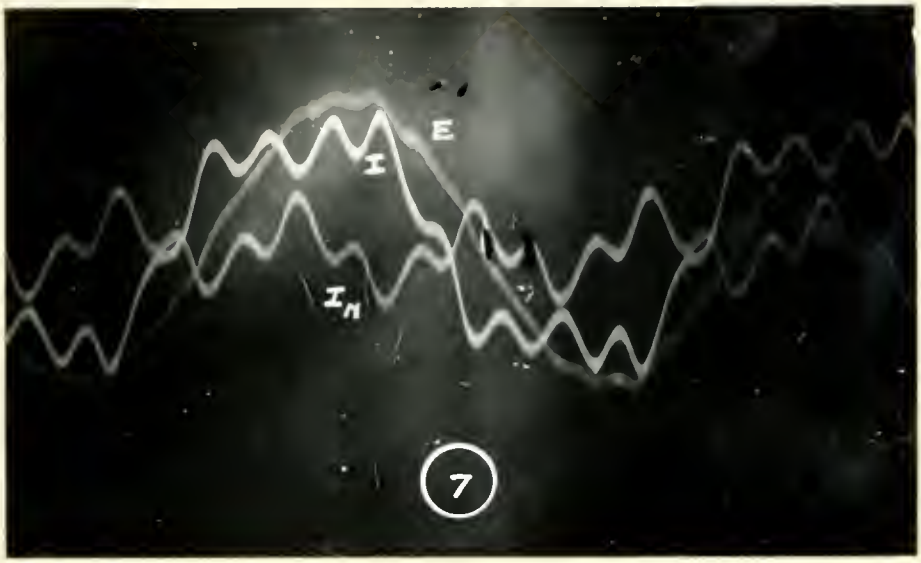
The effect of an increase in neutral current upon its wave shape mentioned in experiment No. 1 is again evident here. A comparison with oscillogram No. 10 shows that the increase in neutral current has strengthened the third harmonic much more than it has the ninth.

The line current wave still shows the effect of the third and ninth harmonics introduced by the neutral current but due to the load on the transformers the fundamental wave has increased in value to such an extent that its distortion is not so pronounced.


E_c
I
I_N
10


E_c
I
I_{11}
11

Oscillogram No. 7 was made in order to compare the wave shapes of line and neutral current using a set of core type transformers with those obtained when using the set of shell type transformers for oscillogram No. 11. The conditions were identical with those under which oscillogram No. 11 was taken but in making the connections the neutral current wave was reversed. The comparison shows that the effect upon the line and neutral currents of the two types of transformers is practically the same.


E
I
I_M
7

Experiment No. 3.

It is now desired to study the neutral current between an alternator having different characteristics than No. 2 which was previously used and a set of three single-phase star connected transformers. In this case it is especially desired to determine the effect on the shape and value of the neutral current and voltage waves due to the operation of the transformers at various flux densities up to the point of saturation, or at least to a value far above normal.

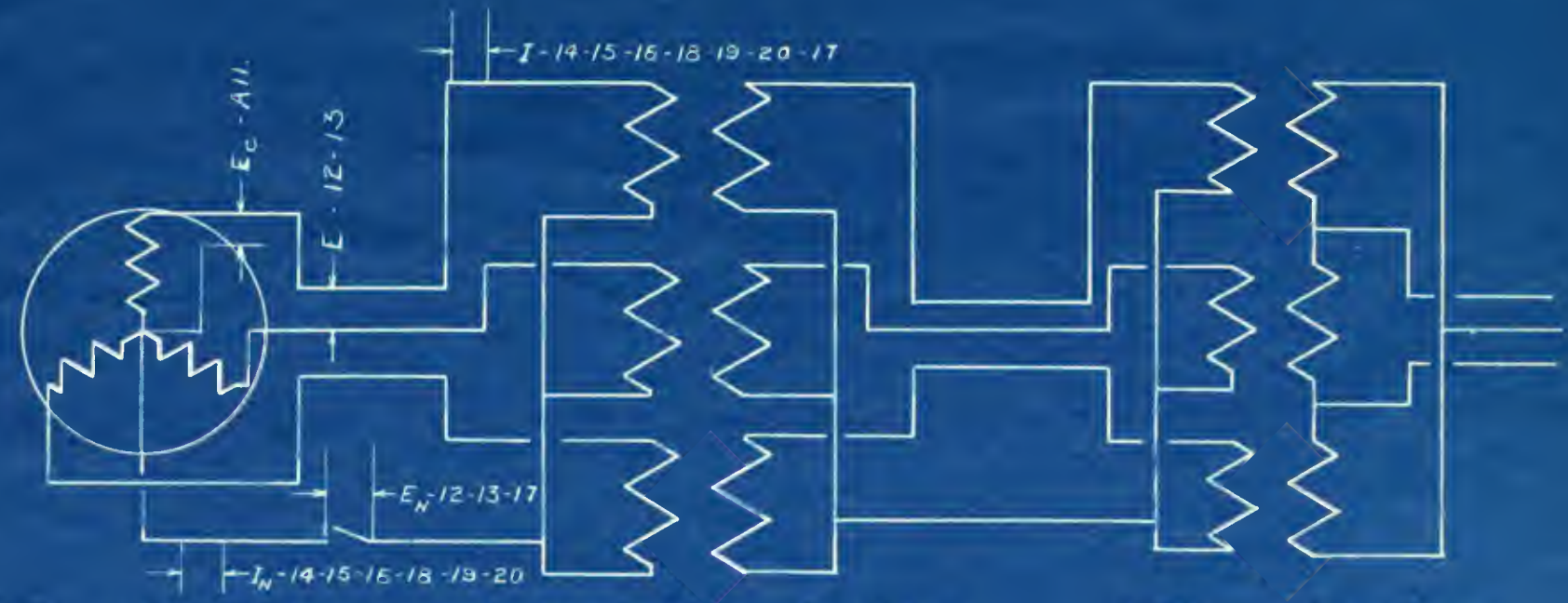
In order to obtain these conditions the apparatus is connected in the following manner. Generator No. 3 is run at a frequency of 30 cycles and excited to give a maximum of 280 volts between line and neutral. The three single-phase Westinghouse shell type transformers are connected to give a ratio of 220 to 1100 volts, and the low sides con-

nected in star to the leads from No. 3 generator. The high sides are also connected star to the high side of a three-phase transformer which steps the voltage down so that an incandescent lamp load may be carried. The banks of lamps are connected in star so that they may receive the correct voltage for their operation.

The generator is then operated at voltages from line to neutral ranging from 140 to 280 volts, and a study is made of the neutral current and voltage under all conditions. The oscillograph is used to get the wave shapes of the various voltages and currents. The neutral is first left open and oscillograms are obtained of the line and coil voltages and voltage between neutrals for the different excitations. A series of runs is made to determine the value of voltage between neutrals at avrious excitations of the generator from a coil voltage of 140 volts to one of 280 volts.

The neutrals are then connected and curves are taken of the line and neutral currents and of the coil voltage. This is repeated for different excitations.

The effect of connecting the high side of the single-phase transformers delta instead of star is now studied. This connection is made, and the lamps are changed to delta connection in order that they may still receive their proper voltage. A study is then made of the wave shapes of the neutral current and the line current. As before, a series of runs is made to determine the value of voltage between neutrals, and of the current circulating through or around the delta at various values of coil voltage. The oscillograms taken are of line current, coil voltage and neutral voltage with the neutral open. The neutral is then closed and the curves of line and neutral current and coil voltage are taken.



Connections for Experiment No. 3 Oscillograms Nos. 12-13-14-15-16-17-18-19-20

Oscillogram Nos. 12 , 13 , 17 , 18 , show the wave shapes of coil voltage and voltage between neutrals taken with No. 3 alternator connected to the three shell type transformers. These oscillograms were obtained to determine the change if any in the neutral voltage wave shape caused by operating the transformer cores at different flux densities.

For oscillogram No. 17 the different values were -

Coil voltage = 200 volts

Neutral " = 58 "

Line current = 3 amperes.

The neutral voltage wave approximates very closely a sine wave of triple frequency but a close examination reveals a very small twenty-first harmonic. The coil voltage wave shows a strong third harmonic combined with a comparatively weak twenty-first and this fact accounts for the high value of the triple frequency neutral voltage.

Oscillogram No. 12 was taken under the same conditions as those for No. 17 except a change of excitation.

The values were -

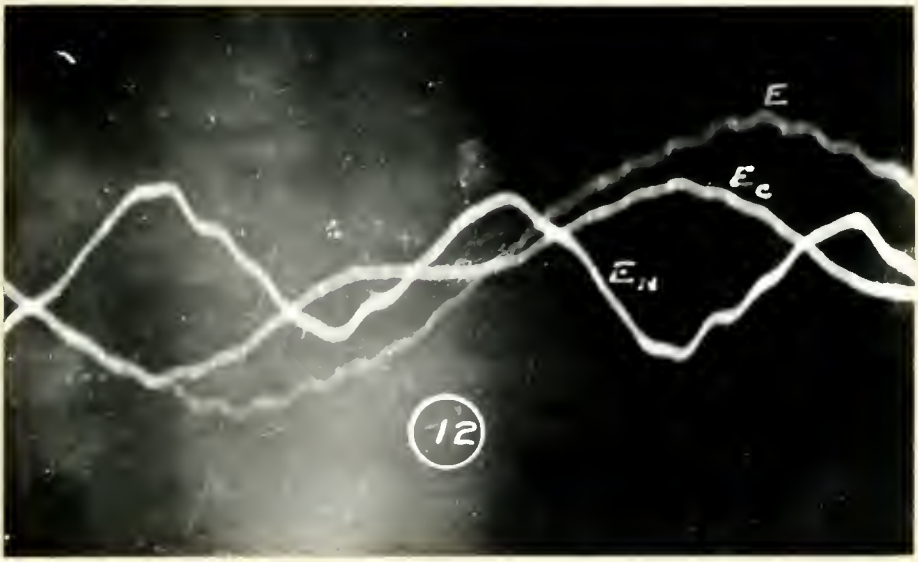
Coil voltage = 230 volts

Neutral " = 71 "

Line voltage = 400 " .

The shape of coil and neutral voltage waves are practically the same as before except that the twenty-first harmonics appear to be stronger. The line voltage wave shows the presence of a small twenty-third harmonic. This twenty-third harmonic also shows in the line current wave of No. 17.

E_c
I
E_M
17


E
E_c
E_M
12

The values of current and voltages when oscillogram No. 18 was taken were -

Line current = 5 amperes

Coil voltage = 260 volts

Neutral " = 100 " .

Through an error the neutral voltage wave is labeled I_n , instead of E_n . All three waves are of practically the same shape as those of oscillogram No. 17.

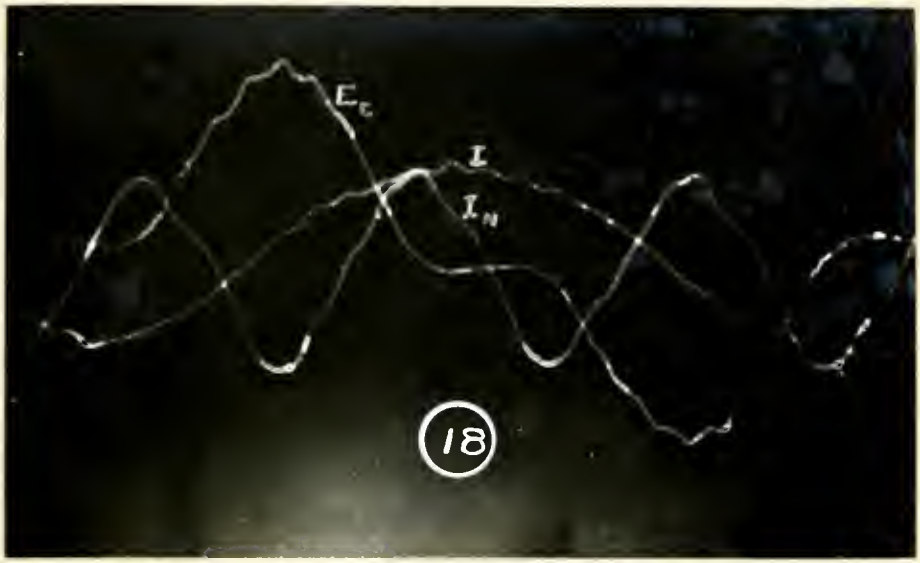
Oscillogram No. 13 shows the three waves when -

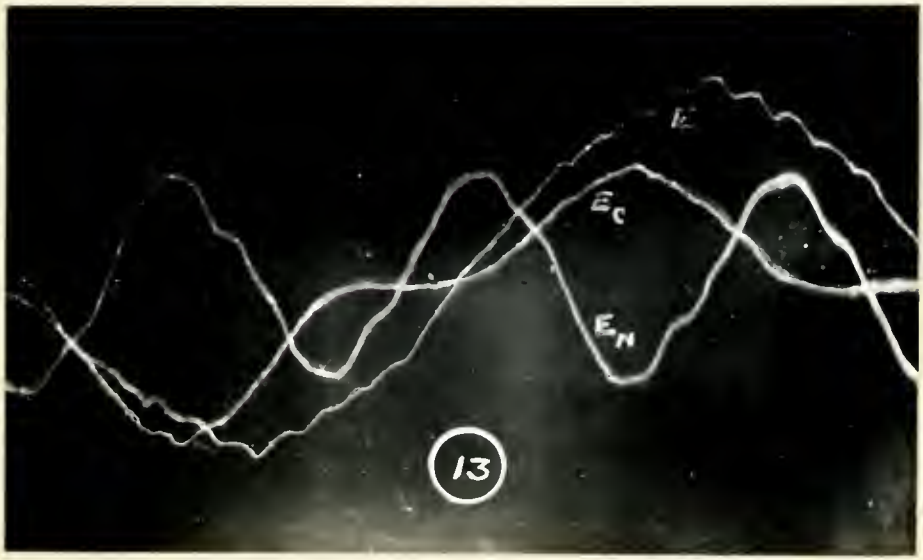
Line voltage = 468 volts

Coil " = 270 "

Neutral " = 110 " .

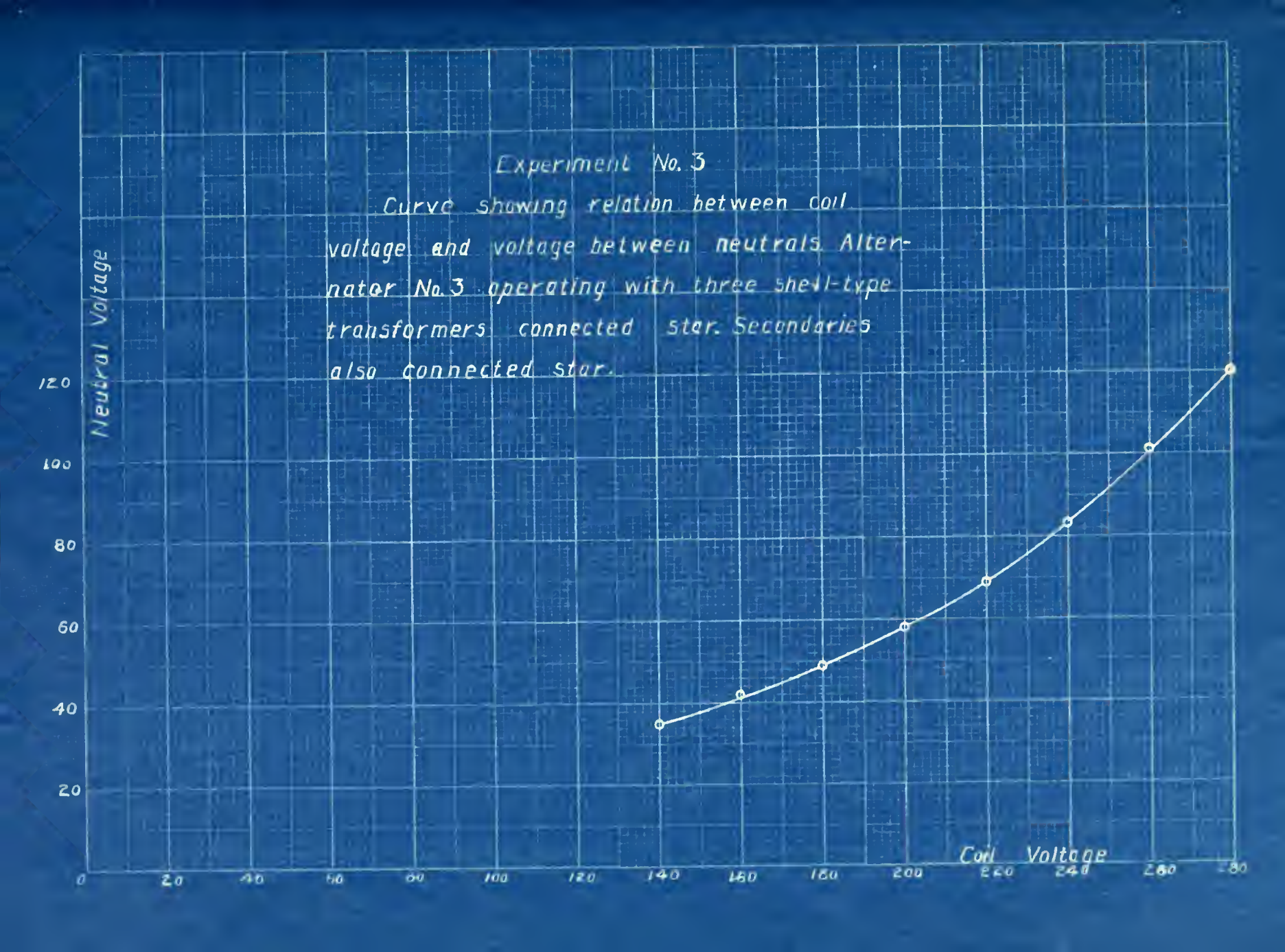
Here again the wave shapes have remained apparently unchanged.


E_c
I
I_H
18


E
E_c
E_H
13

From the results of these four tests , in which all conditions have been kept constant except the generator field excitation , it may be stated that the only effects of changing the flux densities of the transformers have been to increase the difference of voltage between neutrals , and to cause the twenty-first harmonic in this voltage to become more prominent.

To determine the effect upon the voltage between neutrals of varying the generator field excitation a complete test was run. During the test the generator coil voltage was varied from 140 to 280 volts and the line current and the voltage between neutrals noted after each variation. The results of the test are tabulated and a curve drawn showing the relation between the coil voltage and neutral voltage. A study of this curve will show that the increase of voltage between neutrals is nearly proportional to the increase of coil voltage until the normal flux density , which occurs at 220 volts, is reached. Beyond this point the ratio of


Experiment No. 3
Curve showing relation between coil voltage and voltage between neutrals. Alternator No. 3 operating with three shell-type transformers connected star. Secondaries also connected star.
Neutral Voltage
120
100
80
60
40
20
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
Coil Voltage

Oscillograms No. 14, No. 15, and No.16 show the wave shape of coil voltage, line current, and neutral current for the same connection used in the previous oscillograms of this experiment except that the neutral is connected. No. 14 was taken with

coil voltage = 160 volts

line current = 2.5 amperes

neutral current = .25 amperes

The line current wave is approximately a sine wave. The neutral current wave is of triple frequency and also approximates a sine wave.

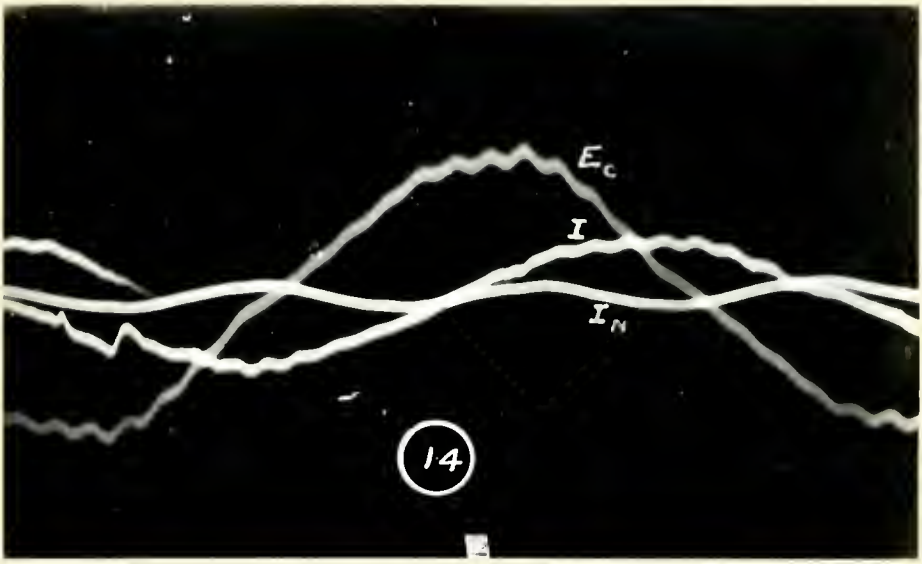
For oscillogram No. 15

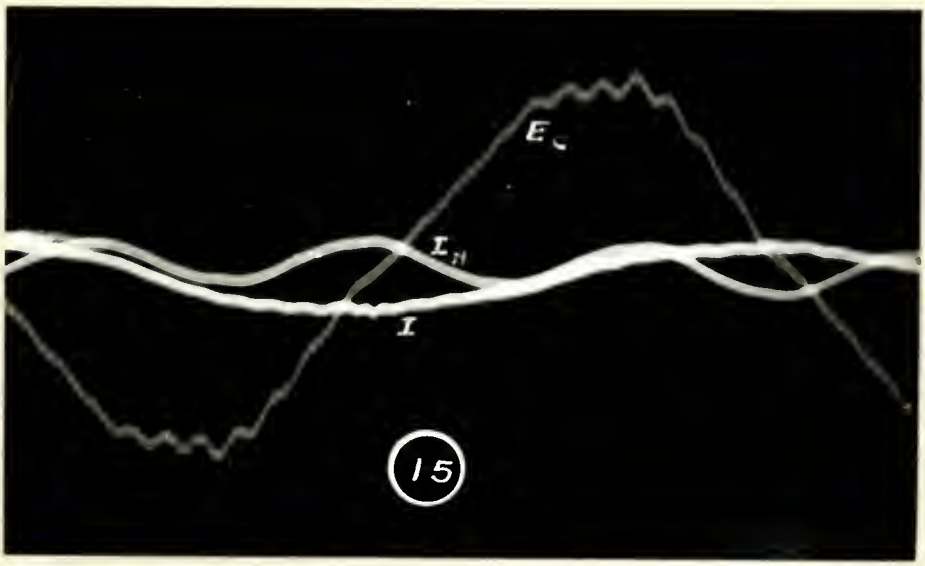
coil voltage = 220 volts

line current = 3.75 amperes

neutral current = .5 amperes

This increase in excitation has apparently had no effect upon the wave shapes.


E_c
I
I_N
14


E_c
I_N
I
15

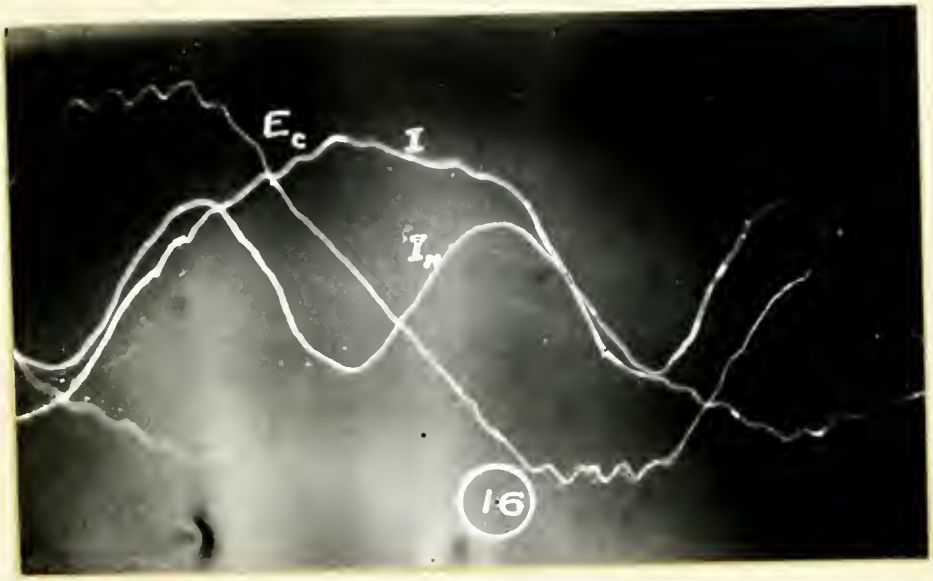
The film from which No. 16 was printed was so dim that it had to be retouched. As a result it is somewhat inaccurate, but shows that the wave shapes have not materially changed. The values were

coil voltage = 280 volts

line current = 6 amperes

neutral current = 1.4 amperes

These three tests further verify the results obtained in the first part of this experiment since the wave shapes have remained unchanged throughout the range of excitations.


E_c
I
I_m
16

In order to study the effect upon the neutral current caused by connecting the secondaries of the three transformers delta instead of star, oscillograms No. 19 and No. 20 were taken. All other connections remained as they were in the first part of this experiment. Oscillogram No. 19 shows the coil voltage and line and neutral current waves. Their values at the time the photograph was taken were

coil voltage = 200 volts

line current = 3.5 amperes

neutral current = 6 amperes

It is interesting to note that, although the same alternator and transformers were used in this test that had been used for the previous tests in this experiment, the coil voltage wave shape has been greatly changed. In the previous tests the coil voltage wave consisted of a fundamental combined with a

small twenty-third harmonic. The change in secondary connections has caused the coil voltage wave to become very flat topped with almost straight sides. This shape is accounted for by the combination of the fundamental with a third and a fifth harmonic. As before, a small twenty-third harmonic also appears in the coil voltage.

The open circuit coil voltage wave shape of No. 3 alternator is shown by oscillogram No. 21 to be approximately a sine wave. The change in coil voltage wave shape must have been caused by the line current flowing through the alternator. The harmonics in the line current may be assumed to have acted independently, through armature reactance and reaction against the field, upon the coil voltage and in this manner produced the wave shape shown in No. 19.

The neutral current wave is made up of

a third harmonic and a twenty-first of very small value. The line current wave shape plainly shows the effect of the returning neutral current. It is badly distorted by the third harmonic, and also shows a twenty first.

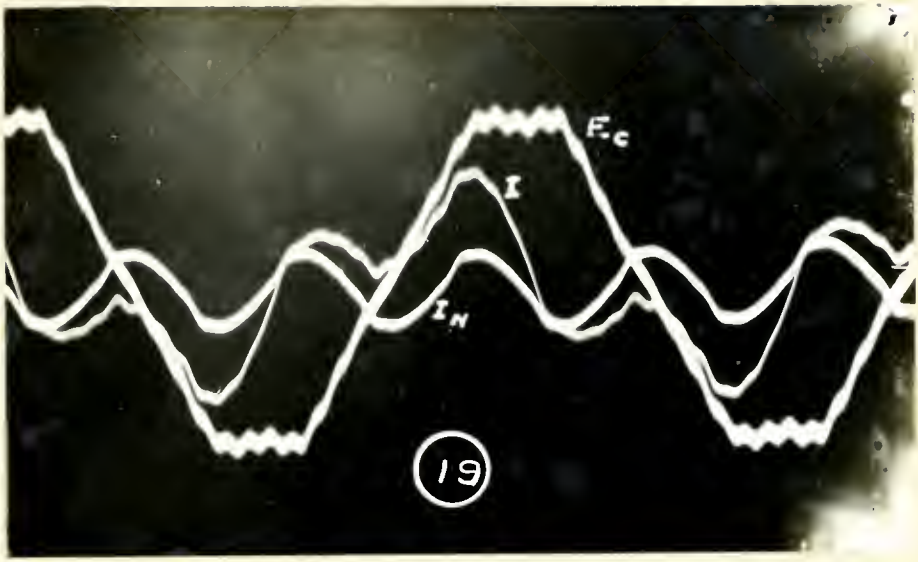
Oscillogram No. 20 was taken under the same conditions as for No. 19 except that the excitation was changed to give

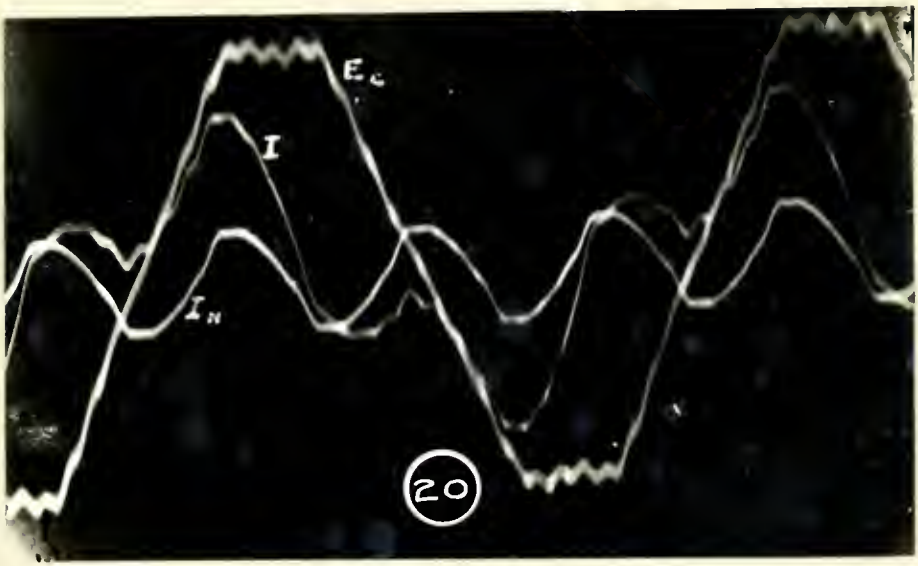
coil voltage = 260 volts

line current = 5.15 amperes

neutral current = 7.4 amperes

This change in excitation has produced no apparent change in the wave shapes.


E_c
I
I_N
19

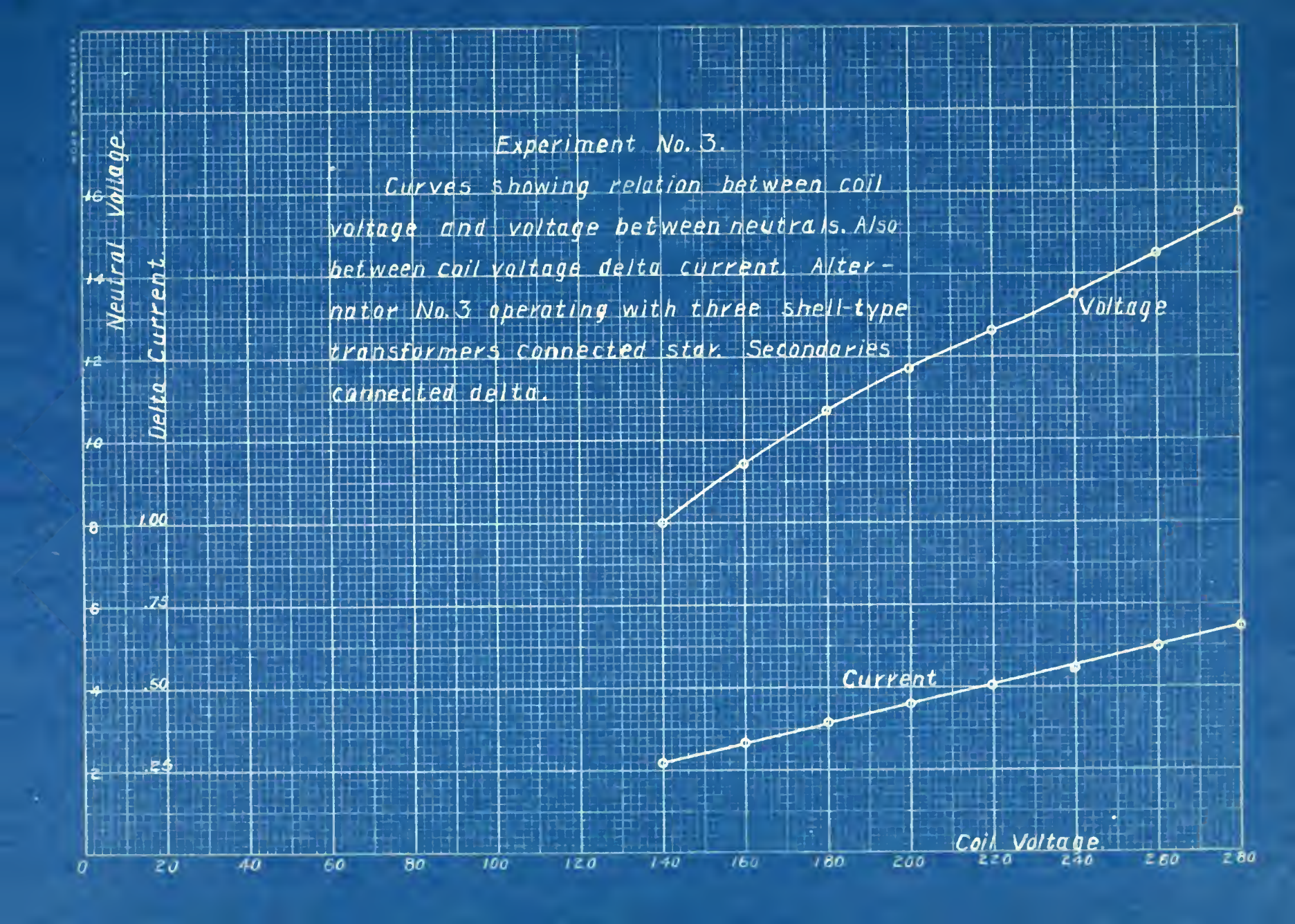

E_c
I
I_N
20

With no load, a series of tests was made at various generator field excitations in order to study the effect on the voltage between neutrals caused by varying the generator coil voltage. As in the tests made with the secondary connected star the coil voltage was varied from 140 to 280 volts. Between these limits the voltage between neutrals varied from 8 to 15.5 volts, and its rate of increase is approximately proportional to the rate of increase of coil voltage. The following curve shows the relation between the neutral voltage and the coil voltage. These results are quite different from those obtained with the transformer secondaries connected star both in value and rate of increase.

In order to know the effect of these changes of coil voltage upon the current circulating in the delta of the transformers an ammeter was placed in one side of the

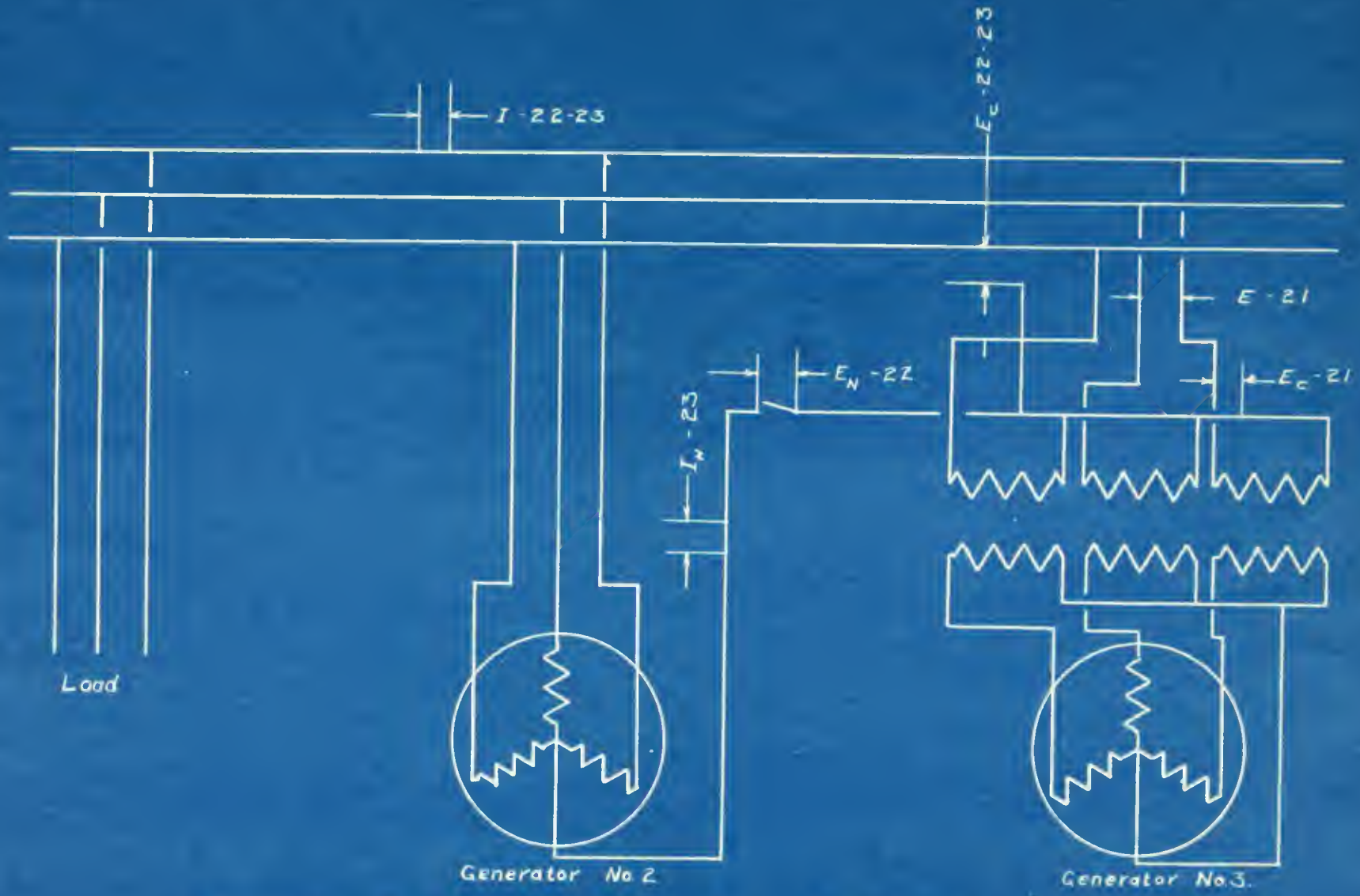
delta, and the value of current circulating at each value of coil voltage was noted. These values are plotted with delta current as ordinates and coil voltage as abscissas.

Coil voltage	Neutral volt.	Delta Amps.
140	8	.27
160	9.4	.33
180	10.7	.394
200	11.7	.448
220	12.6	.51
240	13.5	.566
260	14.5	.624
280	15.5	.680


Experiment No. 3.
Curves showing relation between coil voltage and voltage between neutrals. Also between coil voltage delta current. Alternator No. 3 operating with three shell-type transformers connected star. Secondaries connected delta.
Neutral Voltage.
Delta Current.
Voltage
Current
Coil Voltage.
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
16
14
12
10
8
6
4
2
1.00
.75
.50
.25

Experiment No. 4.

A study is now made of the neutral currents between No. 3 and No. 2 alternators. As a preliminary to this, oscillograms are taken of the line and coil voltage waves of No. 3 generator. In order to parallel these machines it is necessary to step down through transformers from No. 3 generator. The correct phase rotation is determined, and the machines are synchronized by means of lamps. A small balanced load of incandescent lamps was fed from the busses. The neutral connection is left open and oscillograms are taken of the coil voltage, voltage between neutrals, and line current. The neutral is then closed and the wave shape of the neutral current is taken along with that of the line current and of coil voltage.



Connections for Experiment No. 4 Oscillograms Nos. 21-22-23

Oscillogram No. 21 shows the wave shapes of coil and line voltage of alterternator No. 3 operating without load and under normal conditions.

Both waves are practically sine waves although a small twenty-third harmonic shows in each .

Oscillogram No. 22 is a photograph of the wave shapes of coil voltage , line current , and voltage between neutrals taken with No. 2 and No. 3 alternators operating in parallel and supplying a small lamp load.

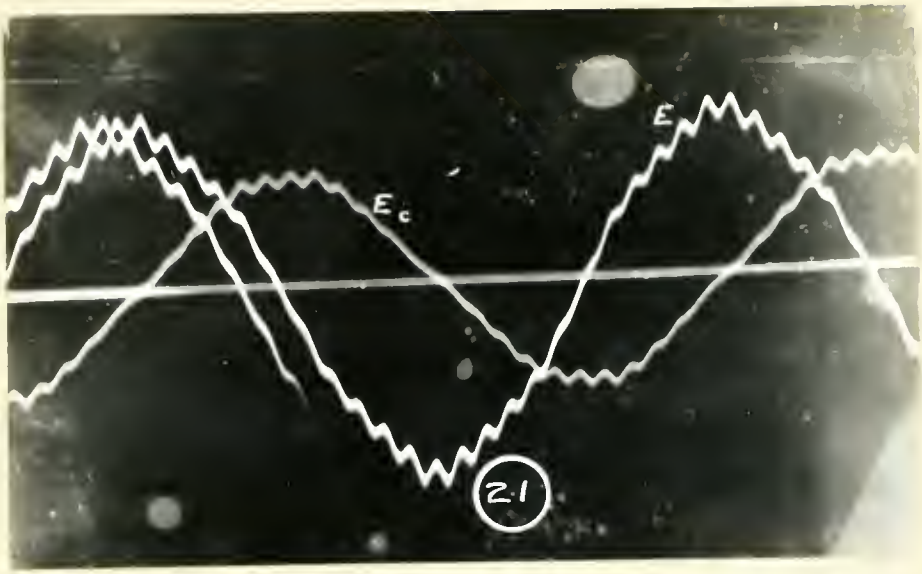
The values were -

Coil voltage = 63.5 volts

Neutral " = 10 "

Line current = 23.25 amperes.

In general the coil voltage wave is shown to be a combination of the coil voltage waves of the two machines as shown in oscillograms No. 21 and 1. The twenty-third harmonic from alternator No. 3 still appears but the wave shape is quite similar to the wave of alternator No. 2 although the thirteenth harmonic is not distinguishable. The line current wave also shows a twenty-third harmonic. The neutral voltage wave is composed chiefly of a third harmonic. There is also a ninth harmonic plainly showing and a very small fundamental.


E
E_c
2.1

E_c
I
E_n
2.2

Oscillogram No. 23 shows the effect of closing the neutral connection between the two alternators operating under the same conditions as for oscillogram No. 22. The values were -

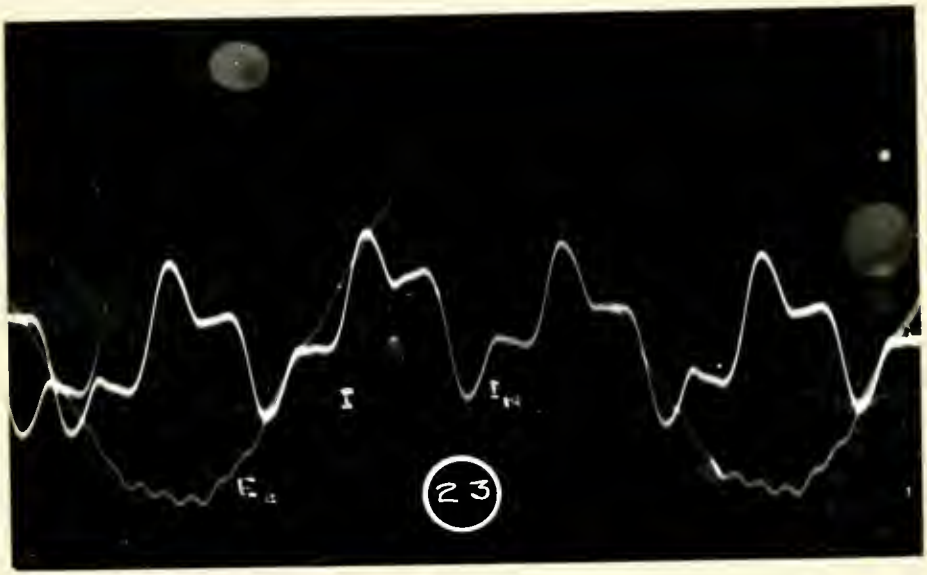
Line current = 23.5 amperes

Neutral " = 8.85 =

This has caused practically no change in coil voltage and line current wave shapes. The neutral current wave shape has been changed from that shown in oscillogram No.22 by a reduction in the comparative value of the ninth harmonic.

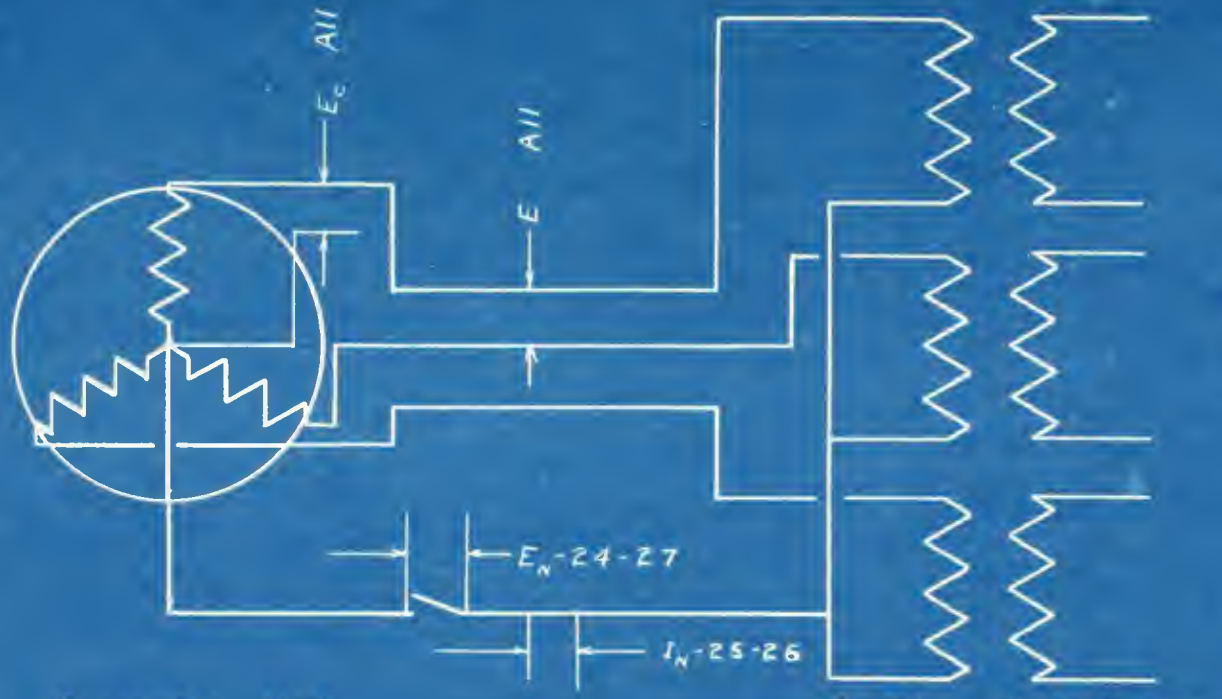
The line current wave shapes shown in oscillograms Nos. 22 and 23 are of the load current and not that between alternators. This accounts for the fact that the line current wave shape did not change its shape when the neutral connection was closed.

In general , these two dissimilar machines operating in parallel have shown no points different than were shown by Nos. 1 and 2 alternators operating in parallel.


23

Experiment No. 5.

In order to study the neutral current and voltage between a three-phase generator connected star to a three-phase transformer, No. 3 generator is connected star to the high side of a three-phase core type transformer, and the low side of the transform er which is connected delta is left open. With the neutral connection open the shapes and values of the line voltage, coil voltage, and neutral voltage are taken. Then the neutrals are connected and the value and shape of the line voltage, coil voltage, and neutral current are taken. For a comparison the same tests are made using No. 2 generator stepped up through three single-phase transformers instead of No. 3.



Connections for Experiment No. 5 Oscillograms Nos. 24-25-26-27

Oscillogram No. 24 shows the wave shapes of line voltage, coil voltage, and voltage between alternator and transformer neutrals. The line and coil voltage waves show the presence of a twenty-third harmonic. The neutral voltage wave is made up principally of a third harmonic, although a fundamental, a ninth, a fifteenth, and a twenty-first are also evident. The values of voltage are

line voltage = 1350 volts

coil voltage = 780 volts

neutral voltage = 19 volts

With the connections the same as for No. 24, the neutral connection was closed and oscillogram No. 25 taken. The wave shapes are of line voltage, coil voltage, and neutral current.

line voltage = 1350 volts

coil voltage = 780 volts

neutral current = .04 amperes

The line and coil voltage shapes have not been affected by connecting the neutrals. The neutral current wave shape is practically the same as the shape of the neutral voltage wave which caused it.

These two tests give results for a comparison with the results obtained in Experiment No. 3 when operating the same alternator connected star to a set of three single-phase transformers. With the single-phase transformers operating at about 122 per cent of their normal voltage the difference in voltage between their neutral

point and the alternator neutral was 110 volts as shown by the data on page 36 of Experiment No. 3 and by the curve which follows. The neutral current for the same excitation was about 7.5 amperes. The value of 110 volts between neutrals amounts to 23.5 per cent of the line voltage.

With the three-phase transformer operating at about 100 per cent of its normal voltage the voltage between neutrals was 19 volts or only 1.41 per cent of the line voltage. The neutral current was only .04 amperes as compared to 7.5 amperes in the former test.

In order to make a further comparison, No. 2 generator and a set of step up transformers was used with the three-phase transformer and oscillograms of line voltage, coil voltage, neutral voltage, and neutral current were obtained.

E
E_c
E_N
24

E
-E
nI
25

With the connections as outlined on the preceding page oscillogram No. 27 was taken. It shows the wave shapes of line voltage, coil voltage, and neutral voltage. The line and coil voltage waves have a thirteenth harmonic present. Their values at the time the photograph was taken were

line voltage = 1400 volts

coil voltage = 810 volts

neutral voltage = 5 volts

The neutral voltage wave is composed chiefly of a fundamental. There are also present a third and a thirteenth harmonic. This is the first time in the entire set of experiments where an oscillogram shows a harmonic in the neutral voltage other than a third or a multiple thereof. The presence of this thirteenth harmonic in the neutral voltage wave is accounted for in the same manner as that of the fundamental. This was

explained in the discussion of oscillogram No. 6 Experiment No. 1.

In this test the neutral voltage is only .35 percent of the line voltage with the transformer operating at 127 per cent of its normal voltage rating.

Oscillogram No. 26 was taken under the same conditions as those for No. 27 except that the neutral connection was closed and the neutral current wave shape obtained in place of the neutral voltage wave shape. The values were

line voltage = 1400 volts

coil voltage = 810 volts

The value of the neutral current was so small that it could not be measured with a very low reading ammeter used with a 20 :1 current transformer.

The wave shapes are practically the same as in No. 27. They all show a thirteenth harmonic quite distinctly.

E
27

E
26

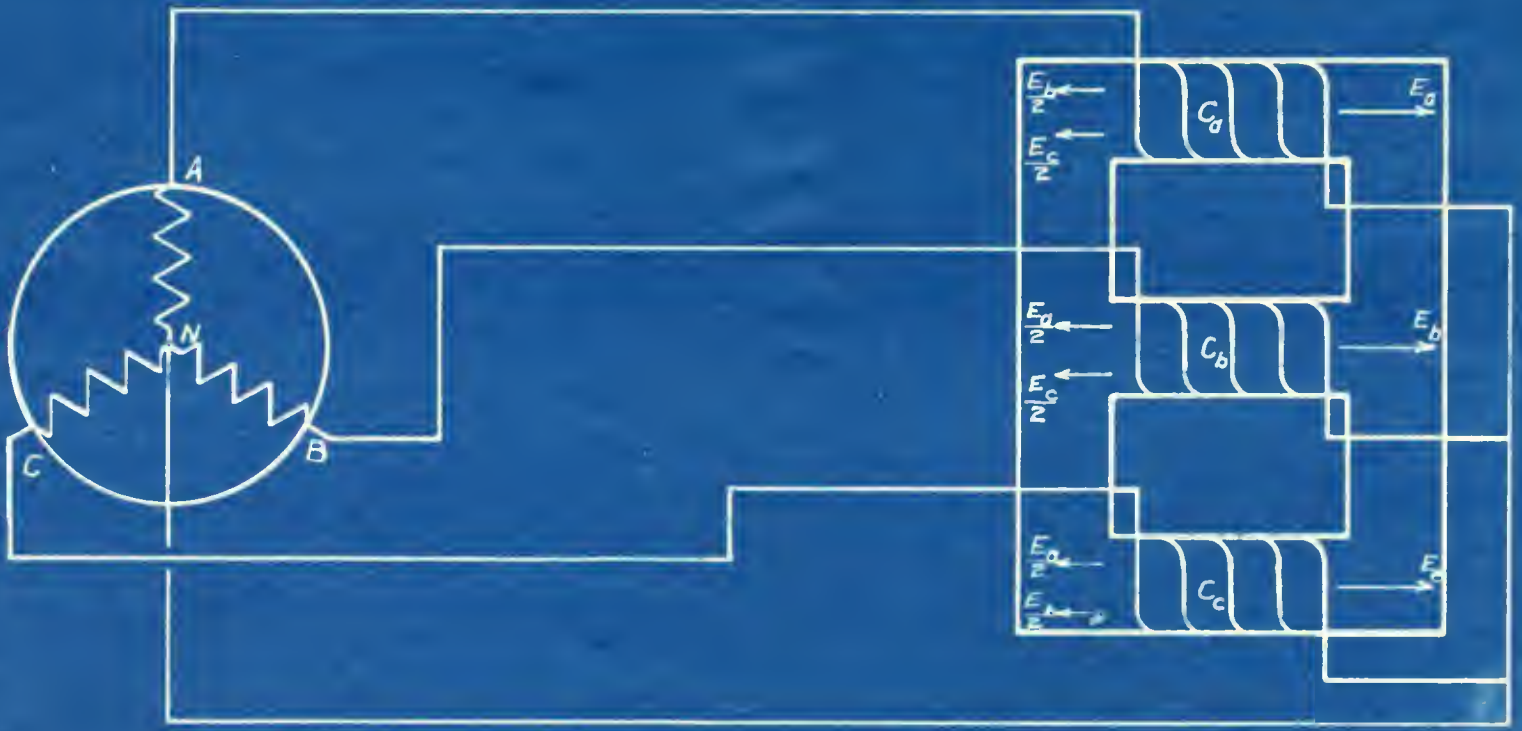
During these four tests the secondary of the three-phase transformer was left open so that no secondary current might flow through the delta and affect the primary side. This condition is equivalent to the star connected secondary as used in Experiment No. 3.

These tests show that with the three-phase core type transformer the tendency is to eliminate any exchange of neutral current between the alternator and transformer neutrals. When operating a star connected three-phase alternator with a set of single-phase transformers the third harmonics in each coil are in time-phase and their values add. This combined triple frequency voltage forms the greater part of the E.M.F. which causes the neutral current to flow. This has been shown in almost every oscillogram of the preceding experiments.

The following discussion will show how the three-phase core type transformer eliminates this third harmonic and thereby practically eliminates the current flowing in the neutral. The accompanying blue print represents the most simple form of a three-phase star connected core type transformer connected to an alternator. Suppose in the voltage generated in each coil of the alternator there appears along with the fundamental voltage wave a wave of triple frequency voltage. In the transformer coils these three triple frequency voltages are in time-phase and equal in value. Let E_a, E_b, and E_c, represent these voltages in coils AN, BN, and CN respectively.

Considering first the effects of the voltage E_a, we may assume that the flux which it produces divides equally in the cores C_b and C_c. The windings being symmet-

rical, these fluxes in C_b and C_c induce in the windings around these cores a voltage eb each equal to one-half the value of E_a, and which is opposed to the applied triple frequency voltage. In the same manner E_b induces voltages of one-half its value in the coils around C_a and C_c. Also E_c induces voltages in the coils around C_a and C_b equal to one-half its value. In all cases these induced voltages oppose the applied. That is, triple frequency voltage generated in the machine is at once opposed by an equal triple frequency voltage in the transformer. Therefore the neutral current, which is composed chiefly of triple frequency harmonics caused by these unopposed triple frequency voltages. does not circulate.


A
N
C
B
$\frac{E_b}{2}$
$\frac{E_c}{2}$
C_a
E_a
$\frac{E_a}{2}$
$\frac{E_c}{2}$
C_b
E_b
$\frac{E_a}{2}$
$\frac{E_b}{2}$
C_c
E_c

Summary.

These experiments have brought out the following facts:

If for any reason the neutral current, which is made up of the third harmonic and multiples thereof flowing between two alternators operating in parallel, or between an alternator and a set of transformers is increased, the third harmonic increases at a greater rate than its multiples do.

An increase in the difference of field excitation of two alternators operating in parallel also increases the Emf. appearing between their neutral points.

The coil voltage wave of an alternator or transformer may contain any odd harmonic. but only the odd harmonics other than the third and its multiples can exist in the line voltage wave.

The effects of core and shell type transformers on the line and neutral cur-

rents are practically the same.

The operation of sets of single-phase transformers - both sides being connected star - at higher voltages than normal tends to increase the flow of current between the transformers and the alternator. Up to normal value of voltage the increase of voltage between neutrals is nearly proportional to the increase of coil voltage. Beyond this point the ratio of the rate of increase of the voltage between neutrals to that of the coil voltage rapidly increases. If the secondaries are connected delta the neutral current flowing between the alternator and the transformer primaries is greatly decreased and the rate of increase as the alternator voltage is raised is practically constant. This decrease in neutral current is evidently caused by the current circulating in the secondaries which are connected delta.

Due to the magnetic action within the core of a three-phase core type transformer the neutral current flowing between its neutral and that of the alternator is practically eliminated.

Respectfully submitted by

Everett Wilcox Kaiser

Frank Edward Myers